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14. ABSTRACT

Presents a novel optical transducer concept in the initial stages of development that promises to be inexpensive, small, lightweight, highly sensitive and durable. The successful development of this sensor will result in an optical accelerometer with resolution under 1 μg ($1g = 9.8\ m/s^2$), which is two to three orders of magnitude more sensitive than current state-of-the-art MEMS-based accelerometers. This accelerometer is also expected to have a wide dynamic range with a resolution under 1 μg at 100 Hz and improved low frequency response over existing MEMS technologies. This will yield much improved velocity and acceleration aiding to GPS tracking loops under high dynamic conditions, permitting continued low bandwidth tracking, a concomitant mitigation of external noise, and an increased jamming immunity. Also, the successful development of this accelerometer may enable the use of Distributed Tactical Navigation Tools (DISTANT) IMUs, where distributed ultra-sensitive accelerometers may replace one or more expensive gyroscopes in an integrated IMU system.

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Electro-Optical Ultra Sensitive Accelerometer

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Abstract

We present a novel optical transducer concept in the initial stages of development that promises to be inexpensive, small, lightweight, highly sensitive and durable. The successful development of this sensor will result in an optical accelerometer with resolution under 1 μg (1g = 9.8 m/s^2), which is two to three orders of magnitude more sensitive than current state-of-the-art MEMS-based accelerometers. This accelerometer is also expected to have a wide dynamic range with a resolution under 1 μg at 100 Hz and improved low frequency response over existing MEMS technologies. This will yield much improved velocity and acceleration aiding to GPS tracking loops under high dynamic conditions, permitting continued low bandwidth tracking, a concomitant mitigation of external noise, and an increased jamming immunity. Also, the successful development of this accelerometer may enable the use of Distributed Tactical Navigation Tools (DISTANT) IMUs, where distributed ultra-sensitive accelerometers may replace one or more expensive gyroscopes in an integrated IMU system.

Introduction

High sensitivity accelerometers are critical for the next generation navigation and guidance systems including tight coupling to existing GPS engines, pressure sensors, and platform stabilization for space applications. The impetus for a MEMS-based inertial accelerometer is based upon the hopes of realizing a low cost, small, lightweight and highly sensitive alternative to existing macro-scale approaches. The successful fabrication of a low cost, high sensitivity MEMS accelerometer will result in new applications for both consumer and military users that aren't feasible with current technologies. Examples include personal hand held navigators for consumer applications and the enhancement of existing navigation systems by arraying sensors to either reduce the noise floor or increase input range and frequency response of the system.

Numerous MEMS devices used for the detection of motion, position, pressure and temperature rely upon the precise measurement of the displacement of a proof mass attached to a spring. To detect these displacements several techniques have been employed including measurement of charge on a variable capacitor [1-4], change in optical transmission through a Bragg grating [5], change in resistance of a piezoresistor [6-9] and most recently measurement of tunneling current through a well-controlled airgap [10-13]. Of these techniques, tunneling displacement sensors hold the best promise for realizing small, highly sensitive transducers required for navigation and acoustic applications. Tunneling transducers take advantage of the exponential sensitivity in tunneling current to the tunneling gap distance in order to realize appreciable changes in current with input acceleration. Typical steady state tunneling current is approximately 1-2 nA [14]. In order to achieve this steady state current, an airgap on the order of approximately 10 Å must be maintained via force rebalancing. Due to the limited tunneling area (one metal atom on the surface of each side of the airgap), larger tunneling currents are difficult to obtain. In addition, tunneling transducers may have high temperature sensitivity since thermal expansion / contraction and thermal expansion coefficient mismatches can alter the tunneling gap distance [15]. Finally, tunneling accelerometers are reported to have a significant 1/f (flicker) noise contribution and a high variability in the tunneling barrier height [16].

We present a novel optical transducer concept for the precise measurement of a proof mass attached to a spring that has raw sensitivity greater than that of a tunneling transducer. The concept involves the monolithic integration of a Fabry-Perot interferometer and a photodiode on a (100) Si substrate using surface micro-machining techniques resulting in a compact device with minimal parasitic elements. MEMS-based Fabry-Perot Interferometers have recently been investigated for use in numerous applications including chemical sensing [17], Wavelength Division Multiplexed (WDM) optical communications [18], and pressure sensors [19]. The monolithic integration of a Fabry-Perot interferometer and a p-n photodiode on a (111) silicon substrate has been reported elsewhere for use as a versatile switch and amplifier [20]. The monolithic integration results in a versatile optoelectronic device possessing active transistor-like characteristics that can be used as the input stage of a low noise amplifier. We have named the device MEMS Ultra-Sensitive Accelerometer (MEMS USA).

Conceptual Theory

Like the tunneling transducer, the relative transmission through a Fabry-Perot cavity has an exponential sensitivity to changes in the effective cavity length. A Fabry-Perot cavity first devised by C. Fabry and H. Perot in 1899 utilizes multiple beam interference. In the field of optics it is usually used to measure wavelengths with high precision and study the fine structure of spectral lines. In its simplest form, a Fabry-Perot cavity consists of two optically flat, partially transmissive and parallel mirrors separated by a distance, y(a). For the case where one of the mirrors is allowed to move, the structure is referred to as an interferometer. The two mirrors form an optically resonant cavity whereby the transmission of monochromatic light through the cavity can be made to be highly sensitive to displacement of one mirror with reference to the second fixed mirror. For an ideal Fabry-Perot cavity the two reflecting surfaces are separated by a medium (generally air) with thickness y(a), refractive index n, and absorption coefficient α. Assuming a symmetric structure ($r_{01} = -r_{12}$ and $t_{01} = t_{12}$) with no absorption within the mirrors or the cavity at the wavelength of interest, an analytical expression for the photo-generated current as a function of the effective airgap displacement, y(a), can be obtained.

$$I_{ph} = \Re P_{in} \frac{1}{1+F\,U^2} \tag{1}$$

$$U = \sin\left(\frac{2\pi}{\lambda}\left(n_1 y(a) + n_{ox} d_{ox}\right)\right) \tag{2}$$

In equations (1-2), F is the Finesse of the cavity, P_{in} is the input optical power incident normal to the surface of the upper mirror, $\Re$ is the responsivity of the photodiode in A/W, λ is the wavelength of the incident light, and n_{ox} and d_{ox} are the refractive index and thickness of a silicon dioxide upper mirror. A simple silicon dioxide upper mirror structure is used only as an example here for simplicity. In equations (1-2) it is assumed that the mirrors are lossless and absorption occurs only in the medium between the mirrors.

Figure 1 is a plot of the relative transmission intensity through the Fabry-Perot interferometer as a function of the spacing between the mirrors. The plot was generated using three different values of mirror reflectivity, R=0.2, R=0.5 and R=0.9 corresponding to a Finesse of 1, 8, and 360 respectively. The Finesse is a figure of merit for a Fabry-Perot cavity and is a measure of the wavelength selectivity when used as a filter or displacement sensitivity when used as an inertial system. It is clear in Fig. 1, that small displacements result in large changes in relative transmission of light through the cavity, particularly for large values of Finesse.

For the more general case, the structure may not be symmetric, $r_{01} \neq -r_{12}$ and $t_{01} \neq t_{12}$, the mirrors may be comprised of any number of arbitrary dielectric or metallic layers and absorption may exist anywhere within the structure. In this instance, a characteristic matrix similar to that obtained for transmission line structures needs to be solved for each layer.

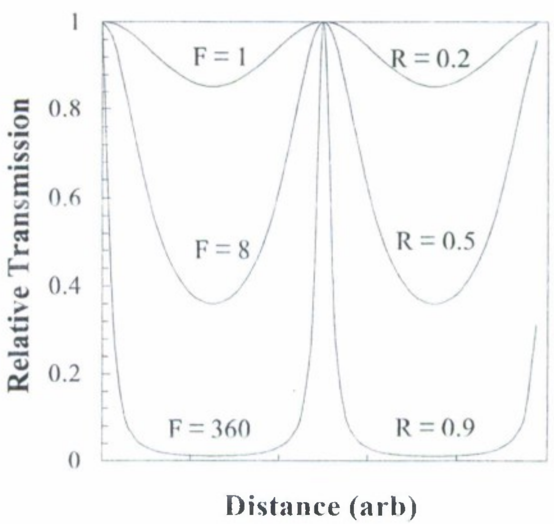

Figure 1. Change in Relative Transmission through a Fabry-Perot cavity as a function of distance for three different reflectivities and corresponding Finesse of the mirrors.

In the absence of absorption and in a resonant condition, the transmission of light through the optical cavity is equal to unity even when the upper mirror itself has a finite reflectivity. This is contrary to what one might expect since it seems reasonable to assume that if the upper mirror has a reflectivity of 0.9, then 90% of the incident light should be lost and not transmitted through the resonant cavity. However, light that is transmitted through the upper mirror and then reflected off the lower mirror is exactly anti-phase with the incident light being reflected from the upper mirror thereby nulling the reflected signal.

By substituting equation (2) into equation (1) and taking the derivative of current, I_{ph}, with respect to acceleration, a, an approximate analytical expression for the current sensitivity is obtained.

$$\frac{dI_{ph}}{da} = -\Re P_{in} \frac{m}{k} \frac{2FUV}{(1+FU^2)^2} \tag{3}$$

$$V = \cos\left(\frac{2\pi}{\lambda}\left(n_1 y(a) + n_{ox} d_{ox}\right)\right) \tag{4}$$

Rewriting equation (3-4) in terms of the photo-generated current a more tractable expression is obtained.

$$\frac{dI_{ph}}{da} \propto \frac{I_{ph}^2 F}{\Re P_{in} \omega_0^2} \tag{5}$$

From equations (3-5) it is clear that in order to increase the sensitivity of MEMS USA any one of the following fabrication / operational changes can be made: Increasing the inertial mass, decreasing the spring constant, increasing the reflectivity of the mirrors thus increasing the Finesse or by increasing the input optical power to the photodiode. It should be noted, in equation (5), that the generated photocurrent varies linearly with the incident optical power, therefore equation (5) will increase linearly with the incident optical power. Figure 2 is a plot of the Finesse as a function of the number of dielectric stacks. From the figure, it can be seen that for approximately every three consecutive dielectric stacks deposited, the sensitivity, as given by equation (5), increases an order of magnitude.

Several techniques exist to linearize the high sensitivity of MEMS USA to displacement in the position of the upper mirror. The first approach is the use of force rebalancing techniques similar to those used in other transducers. The total force acting on the upper mirror is a combination of the input acceleration and the applied potential across the mirror and is kept constant using feedback circuitry. Alternatively, a pair of MEMS USA sensors are operated 180 degrees out of phase with one another such that one resides on an increasing resonant slope while the other resides on a decreasing resonant slope. Using this method, a more linear differential output can be obtained.

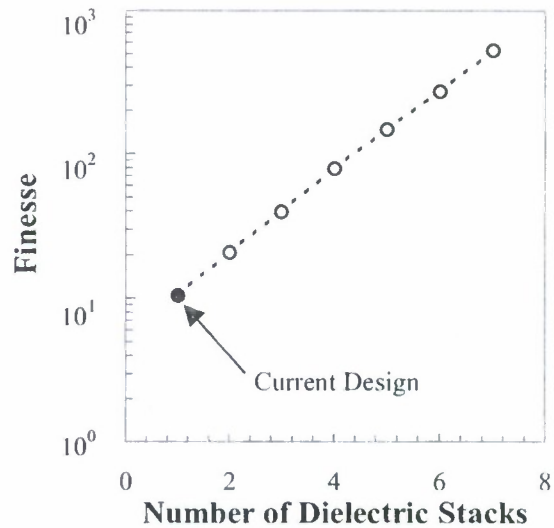

Figure 2. Change in calculated Finesse (reflectivity of the mirrors) as a function of the number of deposited dielectric stacks. The black dot represents the expected Finesse from the design currently under fabrication.

Device Structure

MEMS USA sensors are currently being fabricated using a surface micro-machining process at Space and Naval Warfare Systems Center San Diego's Integrated Circuit Fabrication Facility. Phosphor doped (100) bulk silicon with a sheet resistance of ρ = 10-30 Ω-cm serves as the starting material. Boron implantation is performed to form a shallow one-sided junction so as to collect as much transmitted light into the depletion region of the photodiode as possible thus increasing the responsivity (A/W). A series of well-controlled silicon dioxide and silicon nitride depositions in combination with dry/wet etching is used to form the final structure. A thin semitransparent conductive layer is incorporated into the upper mirror so as to allow for electrostatic control of the airgap spacing between the upper and lower mirrors. The sacrificial layer, in this instance, is approximately 0.8 μm of undoped polysilicon that is later removed using a highly selective Tetra-Methyl Ammonium Hydroxide (TMAH) etch. Figure 3 is a cross-sectional view of an example MEMS USA sensor.

cases, the interface circuitry needs to be integrated with the sensor so as to preserve the full resolution of the device. The monolithic integration of a Fabry-Perot interferometer and a photodiode results in transistor-like characteristics thus forming the input stage to a Low Noise Amplifier (LNA) or a fully differential amplifier.

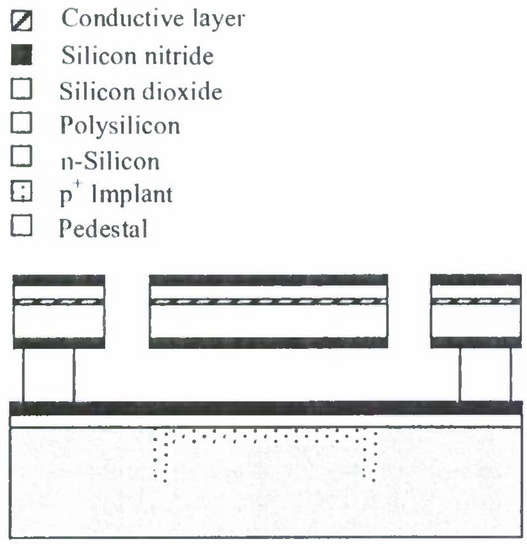

Figure 3. Cross-sectional drawing of an example MEMS USA sensor.

The structure of the mirrors was designed around a peak wavelength of 830 nm in order to utilize the peak responsivity (A/W) of silicon.

The final sensor has three contacts corresponding to the upper mirror and the anode and cathode of the photodiode. The anode of the photodiode also acts as the lower mirror electrode. Potentials applied between the upper mirror and anode contacts results in an electrostatic force that can be used to control the airgap separation in a force rebalance mode and to modulate the photocurrent for use as a active element.

Advantages

Due to their potential small size (<500 μm) as compared to other MEMS-based micro-accelerometers, MEMS USA devices can be arrayed. The ability to array devices has several unique advantages and applications. These include a reduction in the noise floor and hence increased resolution through the time averaging of a NxN array, or adjusting the spring/mirror geometry of individual sensors such that each sensor has a different frequency and/or input acceleration range. In addition, only a single fabrication run is needed to fabricate a wide range of sensors with varying properties for numerous applications where only a single sensor is required.

Previous methods for detecting minute perturbations of a proof mass attached to a spring have revolved around passive transduction methods whereby a change in charge residing across the plates of a capacitor, resistance of a piezoresitive hinge or current from a tunneling tip are detected and amplified by interface circuitry. In many cases, the interface circuitry needs to be integrated with the sensor so as to preserve the full resolution of the device.

One of the distinct advantages of tunneling based transducers is the large change in current due to a change in displacement of the proof mass, expressed in amperes/meter. It has been reported elsewhere [21] that sensitivities as high as 9.4 A/m have been obtained with the tunneling transduction method. MEMS USA devices, however, have the potential to surpass even the sensitivity exhibited by these tunneling transducers. Several unique features of MEMS USA make this possible. First, Fabry-Perot cavities are resonant optical structures and as such can be fabricated to be extremely sensitive to changes in displacement of one mirror in reference to a second fixed mirror. The figure of merit for a Fabry-Perot cavity is the Finesse, which typically describes wavelength selectivity for filtering applications but also describes separation sensitivity for use in inertial systems applications. The Finesse is a function of the mirror reflectivity and can be > 100 using dielectric stack layers deposited using standard IC batch fabrication techniques (see Fig. 2). For filtering applications, Fabry-Perot cavities are often fabricated to examine the fine spectral nature of molecules where sub-Angstrom wavelength resolution is often required [22].

Assuming a Finesse of 10, a responsivity of 0.67 A/W at 830 nm, a photodiode radius of 50 μm, an input optical power density of 10 KW/m^2 corresponding to 80 μW of incident optical power and differential transmission results in a sensitivity of approximately 1000 A/m. This is more than two orders of magnitude larger than that observed for

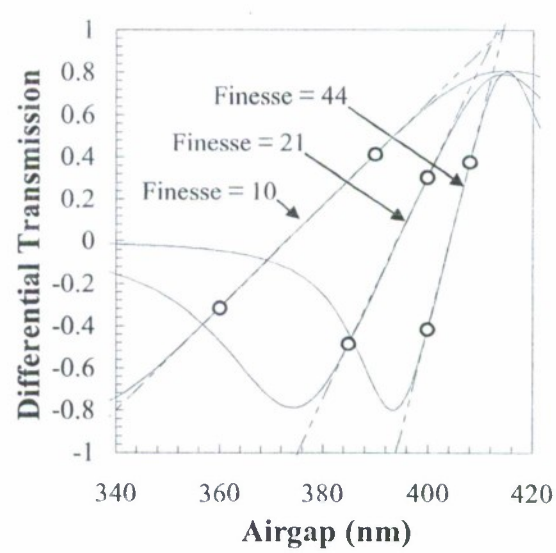

Figure 4. Differential Transmission through a Fabry-Perot cavity as a function of upper mirror displacement for three values of Finesse.

tunneling transducers where tunneling currents are limited to a few nanoamps. Furthermore, this value can be increased by increasing the reflectivity of the mirrors through the deposition of additional dielectric stacks thereby increasing the Finesse, increasing the photodiode radius or by increasing the input optical power. Figure 4 illustrates the increase in differential transmission through the optical cavity as a function of displacement for three different values of Finesse.

Of course raw sensitivity of the sensor is not the only important physical quantity that needs to he considered. The noise floor will determine the true resolution capability of the sensor. In the limit of shot noise within the photodiode and laser source, increasing the optical power incident normal to the upper mirror increases the Signal to Noise Ratio (SNR). The SNR increases because the photo-generated current varies proportionately with the input power whereas the shot noise increases as the square root of input power. The result is a SNR that increases as the square root of input optical power.

For many MEMS devices currently being fabricated, 1/f noise is a serious concern particularly at low frequency operation. This is predominantly an issue for navigation applications where a gradual roll or turn needs to be detected and vibration sensing applications where low frequency excitations need to be measured such as in seismometers or some acoustic sensor applications. Methods exist to electronically modulate the detected signal using custom interface circuitry thus shifting the required information to a higher frequency limiting 1/f noise. In general, the further upstream (close to the input of the signal) a signal is modulated, the hetter low frequency performance it will have. With MEMS USA the signal can he modulated prior to the force-sensing element itself using the laser source thus mitigating thc flicker noise contrihuted.

Sensitivity

The sensitivity of MEMS USA can be determined hy examining the noise sources present within the sensor. In the absence of Brownian motion, shot noise of the photodetector-laser combination and resistivc noise dominate. The resistive noise is determined by the value of the load resistor attached to the MEMS USA sensor. Figure 5 shows the Velocity Random Walk (VRW) as a function of the input optical power for various displacement sensitivities. The displacement sensitivity, including Brownian motion, is determined by the geometrical structure, mass and spring constant, all of which can he adjusted for a particular application. For example, a resonant frequency of 500 Hz results in a displacement sensitivity of approximately 100 nm/g and a corresponding VRW of 80 ng/√Hz at an input power level of 100 μW.

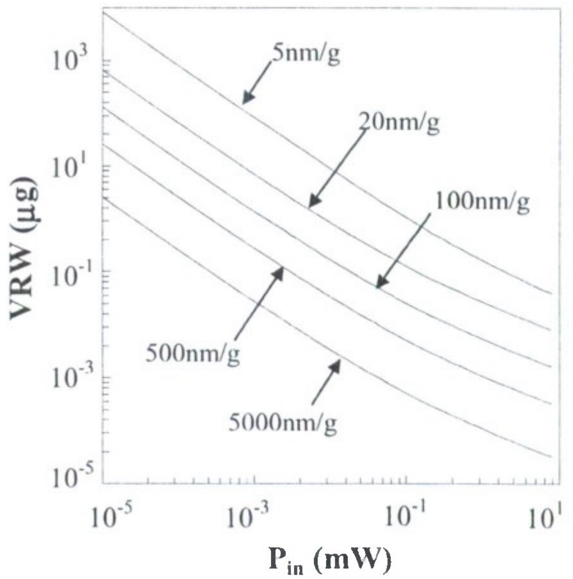

Figure 5. Change in Velocity Random Walk (VRW) as a function of the input optical power for several displacement sensitivities. Each VRW value was assumed to be a 1-second sample with no averaging.

Distributed Tactical Navigation Tool (DISTANT)

Among all the applications payoffs one would expect for a small, ultra-sensitive, low-cost accelerometer, three are worth special mention. First, accelerometers are one of the two key components in every Inertial Measurement Unit (IMU). The successful development of thc ultra-sensitive accelerometer described in this paper will reduce the size and cost of IMUs enabling the use of quality inertial systems in systems that otherwise would not have this capability, such as hand-held units and small one-man submersibles. Second, the successful development of MEMS USA will provide acccleromcters for improved tight-coupling to GPS engines, especially in the new open-architecture GPS receiver cards under development. MEMS USA also has a very wide dynamic range, compared with conventional state-of-the-art MEMS accelerometers, with a calculated resolution undcr 1 μg at 100 Hz. This will yield much improved velocity and acceleration aiding to GPS tracking loops under high-dynamic conditions. This permits continued low-bandwidth tracking, a concomitant mitigation of external noise, and an increased jamming immunity. Third, the successful development of MEMS USA may permit the realization of DISTANT IMUs, where distrihuted ultra-sensitive accelerometers are able to replace one or more expensive gyroscopes in an IMU.

Gyroscopes are generally the most expensive and complicated component of IMUs. Also, the development of gyroscopes in small packages such as MEMS packages has lagged progress in accelerometer development. The original concept behind DISTANT is that a network of distributed accelerometers can be utilized to yield rotational as well as linear motion. Recently, formal mathematical development of such a methodology, along with model calculations, was performed as part of a SPAWAR Small Business Independent Research (SBIR) Program [23]. The two implementations studied in the SBIR Program included: First, an array of six accelerometers, two each for the x-, y-, and z-axes, were mounted symmetrically around a body. In this configuration the accelerometers yielded a centrifugal acceleration that could be related easily to rotational velocity, in addition to acceleration. Second, an array of 12 accelerometers, four each for the x-, y-, and z-axes, were mounted symmetrically around the body. In this configuration, half of the accelerometers were aligned transverse to the radial direction. The output of the transverse-mounted accelerometers could then be integrated to yield changes in rotational motion, in addition to the centrifugal and linear accelerations.

Simple Distant

Consider, for example, a simple, single-axis implementation where an accelerometer is mounted a distance 'r' from a body's center, oriented transverse to the radius in order to measure circumferential acceleration as the body rotates. If one integrates the change in acceleration as the state of rotation changes, the change in rate or angular velocity, $\Delta\omega$, in rad/s is given by

$$\Delta\omega = \frac{\Delta v}{r} = \frac{1}{r}\int_{t_1}^{t_2} a\,dt = \frac{a(\Delta t)}{r} \qquad (6)$$

where v is the linear velocity about the body center in m/s; r is measured in meters and Δt in seconds.. If we sample the unit at a data rate of 500 Hz, the bias stability of the rate would depend on the bias stability of the acceleration and on the size (r). Table 1 illustrates the gyro quality, measured by bias stability in deg/hr, for example, under various cases. The values of acceleration in the table, 0.1-10.0 μg, are the assumed bias stability of the accelerometer. This range represents the anticipated performance range of the accelerometer with good electronics.

This simple illustration for a single axis is intended to show that distributed accelerometers can yield useful information on rotational rate, especially if the accelerometers are of high quality as those described in this paper.

Table 1. Angular rate (deg/hr) sensitivity as a function of radius (cm) and acceleration (μg) sensitivity.

	r = 1	r = 10	r = 100
a = 0.1	0.04	0.004	0.0004
a = 1.0	0.4	0.04	0.004
a = 10	4.0	0.4	0.04

The two 6- and 12-accelerometer configurations described above are only examples. One could utilize such distributed accelerometers in any array of convenience to derive gyroscopic information on one or more axes. In this way, depending on the application and system parameters, the development of DISTANT methodologies could permit the elimination of one or more gyroscopes from an IMU. In some applications, it may be possible to replace all the gyroscopes with such a distributed network of sensitive accelerometers. With the successful development of MEMS USA and three orders of magnitude reduction in accelerometer resolution, such implementations of distributed accelerometers may be realized in small, low-cost, high-resolution IMUs. Other examples have been cited in the literature where gyroscopic information is derived from acceleration in a useful way [24].

The above discussion focuses on conventional applications of accelerometers and gyroscopes to common platforms. Another application where these small, low-cost, ultra-sensitive accelerometers will find application is in the tight coupling of IMUs to GPS receivers in open-architecture GPS engines. At this time, over 22 air programs are scheduled to receive open-architecture GPS receivers in the Navy, Army and Air Force, including the F/A-18C/D, F/A-18E/F, F-14D, S-3A/B, EA-6B, and the C-2A.

In addition to the major air programs, MEMS USA sensors will have numerous applications in DOD systems both as accelerometers and DISTANT-enabled gyroscopes. According to a recent DoD Weapon System Program Plan, weapon systems slated to receive MEMS-based IMUs include the Small Diameter Bomb (SDB), Wind-Corrected Munitions Dispenser (WCMD), the Joint Standoff Weapon (JSOW) Dispenser Warhead, the JSOW Unitary Warhead, the Joint Direct Attack Munition (JDAM), the Advanced Land Attack Missile (ALAM), the Joint Common Ground/Air Missile (JCM), the Common Kinetic Energy Missile (CKEM), Spike, the Theater High Altitude Air Defense (THAAD Missile, the Joint Air to Air Standoff Missile (JAASM), the Medium Extended Air Defense System (MEADS), the Guided Multiple Launch Rocket System (GMLRS), the Long Range Land Attack Projectile (LRLAP), the Tank Extended Range Munition

Kinetic Energy/Chemical Energy Rocket, the Future Combat System, the Extended Combat System (ECS), the Extended Range Guided Munition (ERGM), the Excalibur, and the Precision Guided Mortar Munition (PGMM).

Conclusions

We have presented a novel optical MEMS-based transducer for the precise measurement of displacement of a proof mass. The concept was shown to have an active pickoff with minimal parasitic elements. Typical calculated sensitivities are greater than those expected for a tunneling based transducer.

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References

[1] N. Yazdi, K. Najafi, "An All-Silicon Single-Wafer Micro-g Accelerometer with a Combined Surface and Bulk Micromachining Process", J. Microelectromechanical Systems, Vol. 9., No. 4, Dec. 2000, p.544-550.

[2] J. Bernstein, R. Miller, W. Kelley, P. Ward, "Low-Noise MEMS Vibration Sensor for Geophysical Applications", J. Microelectromechanical Systems, Vol. 8, No. 4, Dec. 1999, p.433-438.

[3] K.H. Chau, S.R. Lewis, Y. Zhao, R.T. Howe, S.F. Bart, R.G. Marchcselli, "An Integrated Force-Balanced Capacitive Accelerometer for Low-G Applications", Transducers '95, June 25-29, 1995, p. 593-596.

[4] J. W. Weigold, K. Najafi, S.W. Pang, "Design and Fabrication of Submicrometer, Single Crystal Si Accelerometer", J. Microelectromechanical Systems, Vol. 10, No. 4, Dec, 2001, p.518-524.

[5] T. Storgaard-Larsen, S. Bouwstra, O. Leistiko, "Opto-Mechanical Accelerometer Based on Strain Sensing by a Bragg Grating in a Planar Waveguide", Transducers '95, June 25-29, 1995, p.667-670.

[6] D.L. Devoe, A.P. Pisano, "Surface Micromachined Piezoelectric Accelerometers (PiXLs)", J. Microelectromechanical Systems, Vol. 10, No. 2, June 2001, p.180-186.

[7] H. Chen, M. Bao, H. Zhu, S. Shen, "A Piezoresistive Accelerometer with Novel Vertical Beam Structure", Transducers '97, June16-19, 1997, p.1201-1204.

[8] D.L. Devoe, A.P. Pisano, "A Fully Surface-Micromachined Piezoelectric Accelerometer", Trnasducers '97, June 16-19, 1997, p.1205-1208.

[9] B. Puers, L. Reynaert, W. Snoeys, W.M. Sansen, "A New Uniaxial Accelerometer in Silicon Based on the Piezojunction Effect", IEEE Trans. On Elec. Dev., Vol. 35, No. 6., June 1988, p.764-770.

[10] C.H. Liu, T.W. Kenny, "A High Precision, Wide-Bandwidth Micromachined Tunneling Accelerometer", J. MicroElectromechanical Systems, Vol. 10, no. 3, Sept. 2001, p. 425-433.

[11] C. Yeh, K. Najafi, "CMOS Interface Circuitry for a Low-Voltage Micromachined Tunneling Accelerometer", J. Microelectromechanical Systems, Vol. 7, No. 1, March 1998, p. 6-15.

[12] C. Yeh, K. Najafi, "A Low-Voltage Tunneling-Based Silicon Microaccelerometer", IEEE Transactions on Electron Devices, Vol. 44, No. 11, p. 1875-1882, November 1997.

[13] J. Grade, A. Barzilai, J.K. Reynolds, C.H. Liu, A. Partridge, L.M. Miller, J.A. Podosek, T. Kenny, "Low Frequency Drift in Tunnel Sensors", 1997 International Conference on Solid-State Sensors and Actuators, Transducers '97, p. 871-874, June16, 1997.

[14] T.W. Kenny, S.B. Waltman, J.K. Reynolds, and W.J. Kaiser, "Micromachined silicon tunnel sensor for motion detection", Appl. Phys. Lett., Vol. 58, No. 1, p.100, Jan. 1991.

[15] C.H. Liu, A.M. Barzilai, J.K. Reynolds, A. Partridge, T.W. Kenny, J.D. Grade, H.K. Rockstad, "Characterization of a High-Sensitiivty Micromachined Tunneling Accelerometer with Micro-g Resolution", J. Microelectromechanical Syatems, Vol. 7, No. 2, June 1998, p. 235-244.

[16] N. Yazdi, F. Ayazi, K. Najafi, "Micromachined Inertial Sensors", Proceedings of the IEEE, Vol. 86, No. 8, Aug. 1998, p.1640-1659.

[17] J. Han, D.P. Neikirk, M. Clevenger, J.T. McDevitt, "Fabrication and Characterization of a Fabry-Perot Based Chemical Sensor, "Proceedings of the SPIE, Vol.2881, 1996, p.171-178.

[18] M. Frank Chang, M.C. Wu, "Surface Micromachined Devices for Microwave and Photonic Applications", Proceedings of the SPIE, Vol. 3419, 1998, p.214-226.

[19] M.G. Kim, J. Park, S.W. Kang, B.K. Sohn, "A Fiber Optic Fabry-Perot Pressure Sensor with the Si3N4/SiO2/Si3N4 diaphragm Fabricated using

Micromachining Technology", Proceedings of the SPIE, Vol. 3242, 1997, p347-353.

[20] R. Waters, J. Patterson, B. Van Zeghbroeck, "Micromechanical Optoelectronic Switch and Amplifier (MIMOSA)", IEEE J. of Selected topics in Quantum Electronics, vol 5, no. 1, pp. 33-35, JAN/FEB 1999.

[21] T.B. Gabrielson, "Mechanical-Thermal Noise in Micromachined Acoustic and Vibration Sensors", IEEE Transactions on Electron Devices, Vol. 40, no. 5, pp. 903-909, May 1993.

[22] G.R. Fowles, Introduction to Modern Optics, Dover Publications, NY, 1989.

[23] "Realization of DISTANT based on Distributed Array of Semiconductor Accelerometers and Gyros," Final Report, SBIR contract no. N00039-99-C-2229, VeNIS Technologies, Inc., Berkeley, CA, March 2000.

[24] See "Initial Attitude Determination and Correction of Gyro-Free INS Angular Orientation on the Basis of GPS Linear Navigation Parameters," K.S. Mostov, A.A. Soloviev, T.K. Koo, Proceedings of Intelligent Transportation systems, November 1997; see also, "Gyroless Line-of-Sight Stabilization for Pointing and Tracking Systems," M. Algrain, SPIE's Optical Engineering Journal, April 1994.

Dups

Electro-Optical Ultra Sensitive Accelerometer

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Abstract

We present a novel optical transducer concept in the initial stages of development that promises to be inexpensive, small, lightweight, highly sensitive and durable. The successful development of this sensor will result in an optical accelerometer with resolution under 1 μg (1g = 9.8 m/s^2), which is two to three orders of magnitude more sensitive than current state-of-the-art MEMS-based accelerometers. This accelerometer is also expected to have a wide dynamic range with a resolution under 1 μg at 100 Hz and improved low frequency response over existing MEMS technologies. This will yield much improved velocity and acceleration aiding to GPS tracking loops under high dynamic conditions, permitting continued low bandwidth tracking, a concomitant mitigation of external noise, and an increased jamming immunity. Also, the successful development of this accelerometer may enable the use of Distributed Tactical Navigation Tools (DISTANT) IMUs, where distributed ultra-sensitive accelerometers may replace one or more expensive gyroscopes in an integrated IMU system.

Introduction

High sensitivity accelerometers are critical for the next generation navigation and guidance systems including tight coupling to existing GPS engines, pressure sensors, and platform stabilization for space applications. The impetus for a MEMS-based inertial accelerometer is based upon the hopes of realizing a low cost, small, lightweight and highly sensitive alternative to existing macro-scale approaches. The successful fabrication of a low cost, high sensitivity MEMS accelerometer will result in new applications for both consumer and military users that aren't feasible with current technologies. Examples include personal hand held navigators for consumer applications and the enhancement of existing navigation systems by arraying sensors to either reduce the noise floor or increase input range and frequency response of the system.

Numerous MEMS devices used for the detection of motion, position, pressure and temperature rely upon the precise measurement of the displacement of a proof mass attached to a spring. To detect these displacements several techniques have been employed including measurement of charge on a variable capacitor [1-4], change in optical transmission through a Bragg grating [5], change in resistance of a piezoresistor [6-9] and most recently measurement of tunneling current through a well-controlled airgap [10-13]. Of these techniques, tunneling displacement sensors hold the best promise for realizing small, highly sensitive transducers required for navigation and acoustic applications. Tunneling transducers take advantage of the exponential sensitivity in tunneling current to the tunneling gap distance in order to realize appreciable changes in current with input acceleration. Typical steady state tunneling current is approximately 1-2 nA [14]. In order to achieve this steady state current, an airgap on the order of approximately 10 Å must be maintained via force rebalancing. Due to the limited tunneling area (one metal atom on the surface of each side of the airgap), larger tunneling currents are difficult to obtain. In addition, tunneling transducers may have high temperature sensitivity since thermal expansion / contraction and thermal expansion coefficient mismatches can alter the tunneling gap distance [15]. Finally, tunneling accelerometers are reported to have a significant 1/f (flicker) noise contribution and a high variability in the tunneling barrier height [16].

We present a novel optical transducer concept for the precise measurement of a proof mass attached to a spring that has raw sensitivity greater than that of a tunneling transducer. The concept involves the monolithic integration of a Fabry-Perot interferometer and a photodiode on a (100) Si substrate using surface micro-machining techniques resulting in a compact device with minimal parasitic elements. MEMS-based Fabry-Perot Interferometers have recently been investigated for use in